ONR Post-doctoral Fellowship Award in Ocean Acoustic for Dr. Purnima Ratilal

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LONG-TERM GOALS

The ONR Postdoctoral Award in Ocean Acoustics was awarded to Dr. Purnima Ratilal in October 2002 for research work in conjunction with the ONR-sponsored Acoustic Clutter Program. The long term goal of the Acoustic Clutter Program is to enhance long-range active sonar detection of underwater vehicles, such as submarines, in continental shelf environments with little or no bathymetric relief in the presence of environmental clutter.

OBJECTIVES

The main objective of Dr. Ratilal's research is to contribute to and support the theoretical and experimental efforts of the PI's research group at MIT in the Acoustic Clutter Program. The objectives of the Program are to (1) determine the primary physical mechanisms that cause clutter in active sonar systems operating in littoral environments with little or no bathymetric relief, (2) identify the dominant sources of clutter, and (3) develop techniques to mitigate clutter.

Dr. Ratilal has been actively involved with almost all aspects of the Acoustic Clutter Program from 1999. She was a graduate student of the PI till summer of 2002 and conducted this research as part of her PhD thesis work. During the Acoustic Clutter Reconnanisance Experiment (ACRE) of 2001 off the New Jersey Coast, Dr. Ratilal was actively involved with numerical modelling and simulations [P5,P3,C10] in support of the experiment, design and conduct of the experiment, as well as subsequent analysis of data from this experiment.[P1,P3,C4,C8] The experiment was a great success in demonstrating that discrete clutter events are a major problem for active sonar operations in Continental Shelf environments, even those with little or no bathymetric relief.[P1,P3,C4,C8] She carried out extensive analysis, both theoretical as well as with the experimental data, to determine if sub-bottom geologic features are a possible source of clutter in long-range active sonar.

Another objective of Dr. Ratilal's research is to develop models for the statistics of the forward propagated field in a *waveguide* containing random volume and surface inhomogeneities such as internal waves, fish, bubbles, and seafloor roughness. Dr. Ratilal had previously developed a generalized extinction (forward scatter) theorem for object scattering in a stratified waveguide for her PhD thesis.[P4,P3] In a waveguide containing random inhomogeneities, the attenuation in the mean forward propagated field along with the field variance are expected to depend on the modal extinction [P4] caused by the inhomogeneities in the waveguide. This analytical work provides a useful tool for

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14. ABSTRACT
The ONR Postdoctoral Award in Ocean Acoustics was awarded to Dr. Purnima Ratilal in October 2002 for research work in conjunction with the ONR-sponsored Acoustic Clutter Program. The long term goal of the Acoustic Clutter Program is to enhance long-range active sonar detection of underwater vehicles, such as submarines, in continental shelf environments with little or no bathymetric relief in the presence of environmental clutter.

15. SUBJECT TERMS

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understanding and modelling the spatial covariance of the field between two receivers in a vertical or horizontal line array commonly used in ocean acoustic experiments. In synthetic aperture sonar, this formulation can be applied to estimate the maximum aperture of the synthesized array for enhancing signal-to-noise ratios and hence the cross-range resolution. Beyond this maximum aperture, no further gains can be obtained over the noise when we increase the array length as the signal is no longer coherent across the aperture of the synthesized array.

APPROACH AND WORK COMPLETED

- Design, Conduct and Data Analysis for the Main Acoustic Clutter Experiment 2003.

The Main Acoustic Experiment (MAE) of the Acoustic Clutter Program was recently completed in May of 2003. This experiment was designed to be very controlled and calibrated so that the actual mechanisms and levels for the clutter could be established. Dr. Ratilal played a major role in assisting the PI in organizing, coordinating, designing, and conducting this 3-ship multi-institutional experiment off the New Jersey Coast. She supervised a team of students and other Post-docs from MIT in preparation for the experiment. Her work involved designing and scheduling the ship tracks and waveform transmissions used in the experiment, coordinating resources needed for the experiment from MIT, with our collaborators and with the ships, upgrading of the processing software to optimize data processing at sea, and reduction and analysis of experimental data at sea.

Preliminary analysis of the data shows that high correlation can be observed between locations of prominent clutter in the two-ship long-range active sonar system and locations of densely clustered fish schools found with the fish-finding sonar on a third ship. Many of these correlations were made with data obtained simultaneously within a roughly 2 hour lag. Regions absent of clutter were found to also be absent of significant fish populations. These correlations were observed repeatedly over a period of roughly 3 weeks.[C16,C17] Our measurements also suggest the fish schools tend to favour certain oceanographic fronts and bathymetric contours where food and nutrients are abundant, like the shelf break front. The returns however, will be dynamic and often discrete and target-like in a given vicinity. [C16]

- Statistical Correlation of Clutter with Buried River Channels and with Fish Schools.

In ACRE 2001, it was found that some of the clutter returns appeared to register with known geologic features such as buried river channels, but many prominent and target-like returns also occurred in regions devoid of of any sub-bottom features.[P1,P3,C4,C8] Analysis of the measured clutter data from ACRE 2001 in regions where the sub-bottom geomorphology has been mapped shows that there is no statistically significant difference between the frequency of occurance of repeatable clutter per unit area in areas occupied by buried river channels and that in areas outside of the channels. No compelling evidence could be found to suggest that buried river channels on the New Jersey outer shelf are a significant source of acoustic clutter.[P1] Similar analysis is being made of the data from MAE 2003 by graduate students of the PI, supervised by Dr. Ratilal.

The clutter measured with the long-range sonar is being statistically correlated with data from the fish-finding sonar over the course of the experiment. [C17] The long-range sonar is capable of imaging extensive areas, spanning tens of kilometers, in near real time. In contrast, the fish-finding sonar's single downward-directed beam typically provides a swath of only ten meters width along the ship

track. Dense populations of fish, indicated by prominent returns from the fish-finding sonar are overlain onto the long range acoustic images. The output of the two systems are directly correlated along the track of the fish-finding sonar and the percentage of correlation quantified. Dr. Ratilal is supervising the graduate students of the PI in this work.

- Inversion of Long-Range Acoustic data for fish school distributions

The long-range acoustic data will also be inverted using full waveguide scattering models [P11,C5] to predict the size and density of fish schools over wide areas and with time which will be compared to inversions done locally using data from the fish-finding sonar, as well as results from fish trawls. This analysis will demonstrate a new potential application for long-range sonar as a fast survey method to remotely sense, locate and quantify distant schools of fish and other marine life. Dr. Ratilal will supervise the graduate students of the PI in this work.

- Range-dependent Reverberation Modelling in an Ocean Waveguide

Strong clutter events were measured along certain bathymetric contours close to the edge of the continental shelf in both experiment. This region is known as the shelf break front where the warmer slope water interacts with the cooler shelf water leading to significant oceanographic variability. In ACRE 2001 and during MAE 2003, large schools of fish were found in this area which contains nutrients and food that attracts fish schools. Numerical modelling has already confirmed scattering from fish schools to be a dominant source of clutter especially when the schools are large and densely-populated.[P3,C5] Additional numerical modelling in a range-dependent waveguide is presently conducted to investigate the possibility that internal waves in the shelf break front may lead to some discrete seafloor scattering returns or clutter by focusing energy on the ocean bottom.[C18]

- Dispersion Effects and Charting Error in a Waveguide.

In a shallow water environment the sound field scattered by a target can be complicated by waveguide effects such as multi-modal propagation and dispersion. It has been shown that relying on the sonar equation in a shallow water waveguide can lead to errors in estimating a target's scattering properties. [P2,P3,C11] Furthermore, applying conventional beamforming and matched filtering for target localization can yield errors in range and bearing estimation. To quantify these errors, an analytic expression for active sonar returns after beamforming and matched filtering was derived from waveguide scattering theory. This expression was used to model the beamformer and matched filter output from sub-bottom features. It was found that the maximum range error in charting scattered returns from sub-bottom features in a typical ocean waveguide within 10 km range of the sonar is of the order of 200-m or less.

During ACRE 2001, many prominent and repeatable clutter events were measured in an area close to the buried river channels, but displaced in range and azimuth from the channels by about 1000m. In close proximity were returns from two calibrated targets that were accurately charted in space.[P1] It was unknown previously if the dispersion effects in a waveguide could lead to larger errors in charting objects in the sub-bottom as compared to objects in the water column. The simulation described above was important because it confirmed that the prominent and repeatable clutter measured were charted to their correct locations for the specific geometry and waveguide within an accuracy of 200m and do not

arise from the channels. This information led to the serious consideration of other objects in the environment such, as fish schools, as sources for clutter in the Acoustic Clutter Program. [C19]

- Coherent and Diffuse Scattering in Non-forward Azimuths from Scatterers distributed over wide spatial extents: Seabottom Reverberation and Fish Clutter

The conditions necessary for the field scattered from volume inhomogeneities and surface roughness over wide spatial extents in a waveguide to become diffuse in non-forward azimuths was derived from Green's theorem using a waveguide scattering model. [P3,C5] The conditions depend on the resolution footprint of the sonar system and the wavenumber of the propagating modes. Diffuse scattering leads to a decorrelation of the waveguide modes which allows a statistical description of the scattered field in terms of a smoothly decaying mean intensity with increasing range. When the diffuse scattering conditions are not satisfied, seafloor scattering becomes coherent and leads to the formation of "reverberation rings" or range dependent structure in the reverberant field in range independent environments sometimes observed in high-resolution sonar systems.

The same model was applied to investigate the coherent and incoherent scattering from schools of fish over long ranges in a stratified ocean waveguide. It was found that scattering from fish schools at low frequencies can stand significantly above the reverberation background especially if the school is large and densely populated. This simulation was important as it demonstrated theoretically that fish are a major source of clutter for long-range active sonar in shallow water. As a result of this work, fish survey became an essential part of MAE 2003. [P3,C5]

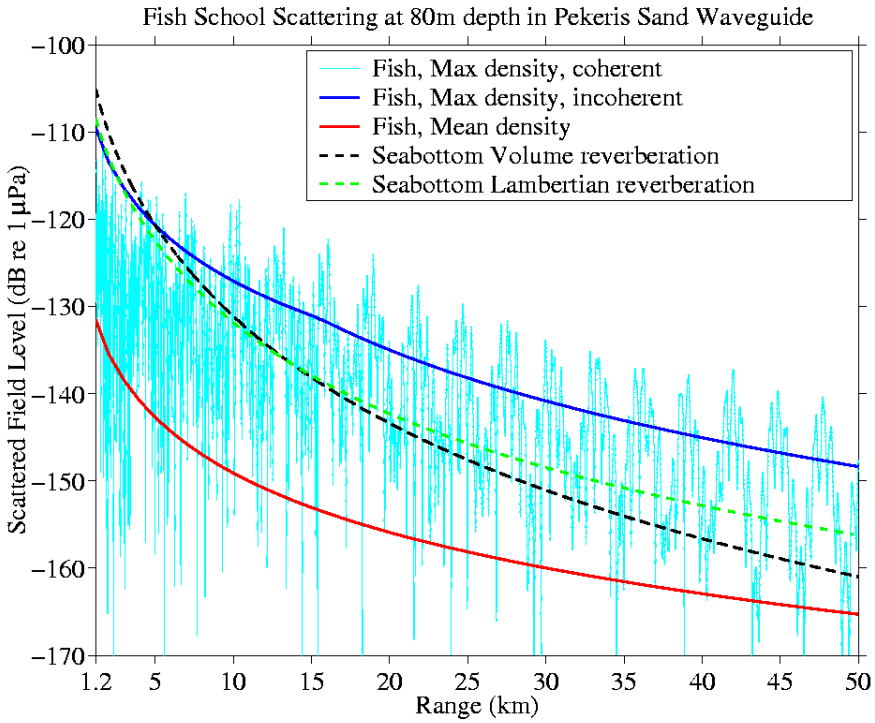

Fig. 1: Simulations using a fully coherent waveguide scattering model shows that scattering from large and densely populated fish schools can stand significantly above diffuse reverberation from the sea bottom.

- Mean and Covariance of Forward Propagated Field in a Waveguide

Analytic expressions for the mean field propagated through a stratified ocean waveguide with random volume or suface inhomogeneities of arbitrary size compared to the wavelength were derived from a wave guide scattering model stemming from Green's theorem. [P3,C1] It is found that multiple scattering through inhomogeneities in the forward azimuth can be succinctly expressed in terms of modal attenuation and dispersion coefficients under widely satisfied conditions. These coefficients depend on the mean scatter function of the inhomogeneities in the medium. Since the inhomogeneities can have an arbitrary distribution in depth, the model can realistically be applied to investigate the mean forward propagated field through internal waves, bubbles, fish schools, as well as sub-bottom anomalies. The Rayleigh-Born single-scatter approximation is applied to model the scattering from volume elements of internal waves. Analytic expressions are obtained for the modal attenuation and dispersion coefficients for each of these scatterers and the effect on the forward propagated field in the waveguide is illustrated numerically. [C2]

Stationary phase approximations is applied to represent the time domain field in terms of the modal group velocities that are smaller than those in a waveguide without inhomogeneities. We show that the dispersion and attentuation effects on the field cannot be explained by heuristic results based on an effective medium sound speed computed using bulk moduli and volume fractions since it does not account for scattering from inhomogeneities in the medium. [C20] The time domain expressions for the forward propagated field are shown to obey causality and are consistent with Kramer-Kronig relations when used in their range of validity.

The spatial coherence between two receivers of the forward propagated field through the waveguide containing random inhomogeneities has also been derived analytically.[C21] It is expressible as a sum of modal covariance terms. Each term depends on (1) the mean modal extinction cross-section of an elemental inhomogeneity of the medium, and (2) the scatter function variance of an elemental inhomogeneity which couples each mode to all the other modes. It shown that the covariance of the forward propagated field varies as the separation between the sensors is increased.

RESULTS AND IMPACT/APPLICATION

The key contribution of Dr. Ratilal's research to the Acoustic Clutter Program and to ocean acoustic research under this proposal is as follows.

- She showed with theoretical modelling using a fully coherent waveguide scattering model that scattering from large and densely populated fish schools can stand significantly above reverberation from the sea bottom making fish school monitoring an important aspect of the MAE 2003.
- Her analysis of the measured clutter data from ACRE 2001 showed that there is no statistically significant difference between the frequency of occurance of repeatable clutter per unit area in areas occupied by buried river channels and that in areas outside of the channels in regions where the sub-bottom has been profiled.
- She derived a consistent theory from first principles for the attenuation and dispersion in the mean forward propagated field and its variance in a shallow water waveguide containing random volume and surface inhomogeneities with an arbitrary distribution in depth.

RELATED PROJECTS

The ONR Acoustic Clutter Program.

REFERENCES/PUBLICATIONS

Refereed Journal Publications:

[P1] P. Ratilal, Y. Lai, D. T. Symonds, L. A. Ruhlmann, J. Goff, C. T. Holland, J. R. Preston, E. K. Scheer, M. T. Sundvic, and N. C. Makris, "Long Range Acoustic Imaging of the Continental Shelf Environment: The Acoustic Clutter Reconnaisance Experiment 2001," submitted to Journal of the Acoustical Society of America (2003).

[P2] P. Ratilal, Y. Lai and N. C. Makris, "Validity of the sonar equation and Babinet's Principle for scattering in a stratified medium," *J. Acoust. Soc. Am*., Vol. 112, 1797-1816 (2002).

[P3] P. Ratilal, "Remote sensing of submerged objects and geomorphology in continental shelf waters with acoustic waveguide scattering," P.hD. thesis, N. C. Makris supervisor, MIT, Cambridge, MA, (2002).

[P4] P. Ratilal and N. C. Makris, "Extinction theorem for object scattering in a stratified medium," *J. Acoust. Soc. Am.*, Vol. 110, 2924-2945 (2001).

[P5] N. C. Makris and P. Ratilal, "A unified model for reverberation and submerged object scattering in a stratified ocean waveguide," *J. Acoust. Soc. Am.*, Vol. 108, 909-941 (2001).

[P6] A. Thode, M. Zanolin, E. Naftali, I. Ingram, P. Ratilal, and N. C. Makris, "Necessary conditions for a maximum likelihood estimate to become asymptotically unbiased and attain the Cramer-Rao lower bound. II. Range and depth localization of a sound source in an ocean waveguide," *J. Acoust. Soc. Am.*, Vol. 112, 1890-1910 (2002).

[P7] P. Ratilal, P. Gerstoft and J. T. Goh, "Subspace approach to inversion by genetic algorithms involving multiple frequencies," *J. Computational Acoust.*, Vol. 6, 99-115 (1998).

[P8} P. Ratilal, P. Gerstoft, J. T. Goh and K. P. Yeo, "Inversion of pressure data on a vertical array to determine the seafloor geoacoustic properties," *J. of Computational Acoust.*, Vol. 6, 269-289 (1998).

Conference Presentations:

[C1] P. Ratilal and N.C. Makris, "Propagation through a stratified ocean wave guide with random volume and surface inhomogeneities, Part I. Theory: Attenuation, dispersion, and acoustic mirages," 144th Meeting of the Acoustical Society of America, Cancun, Mexico, 2-6 Dec 2002.

[C2] T. Chen, P. Ratilal, M. Zanolin and N.C. Makris, "Propagation through a stratified ocean waveguide with random volume and surface inhomogeneities, Part II. Application: Internal waves, bubbles, sub-bottom and seafloor anomalies," 144th Meeting of the Acoustical Society of America, Cancun, Mexico, 2-6 Dec 2002.

[C3] N.C. Makris and P. Ratilal, "Coherent nonlinear scattering mechanisms for ultrasound-stimulated vibro-acoustic spectrography," 144th Meeting of the Acoustical Society of America, Cancun, Mexico, 2-6 Dec 2002.

[C4] N. C. Makris, P. Ratilal, Y. Lai, and D. T. Symonds, "The Geoclutter Experiment 2001: Remote acoustic imaging of sub-bottom and seafloor geomorphology in continental shelf waters," 144th Meeting of the Acoustical Society of America, Cancun, Mexico, 2-6 Dec 2002.

[C5] P. Ratilal and N.C. Makris, "Coherent versus diffuse surface and volume Reverberation in an ocean wave guide: Reverberation rings, modal decoupling, and possible fish scattering in Geoclutter 2001," 144th Meeting of the Acoustical Society of America, Cancun, Mexico, 2-6 Dec 2002.

[C6] S. Lee, P. Ratilal and N.C. Makris, "Model for coherent scattering from a network of buried river channels in a stratified ocean waveguide," 144th Meeting of the Acoustical Society of America, Cancun, Mexico, 2-6 Dec 2002.

[C7] P. Ratilal and N. C. Makris, "Probability of detection and false alarm for target signals measured with seafloor reverberation in a shallow water waveguide," 142nd Meeting of the Acoustical Society of America, Fort Lauderdale, FL, 3-7 Dec 2001.

[C8] N. C. Makris, P. Ratilal, Y. Lai and E. Scheer, "The Geoclutter experiment: Remotely imaging sub-bottom geomorphology in shallow water," 142nd Meeting of the Acoustical Society of America, Fort Lauderdale, FL, 3-7 Dec 2001.

[C9] P. Ratilal and N. C. Makris, "Extinction theorem for object scattering in a stratified medium," 140th Meeting of the Acoustical Society of America, Newport Beach, CA, 3-8 Dec 2000. Also presented at the 17th International Congress on Acoustics, Rome, Italy, 2-7 Sep, 2001.

[C10] P. Ratilal and N. C. Makris, "A unified model for reverberation and submerged target scattering in shallow water," 139th Meeting of the Acoustical Society of America, Atlanta, GA, 30 May-3 Jun 2000. Also presented at the Fifth European Conference on Underwater Acoustics, Lyon, France, July 2000.

[C11] P. Ratilal, Y. Lai and N. C. Makris, "Validity of the sonar equation and Babinet's principle for object scattering in a shallow water waveguide," 138th meeting of the Acoustical Society of America, Columbus, OH, 1-5 Nov 1999.

[C16] N. C. Makris, P. Ratilal, Y. Lai, S. Lee, D. T. Symonds, L. A. Ruhlmann, R. W. Nero, J. R. Preston, E. K. Scheer and M. T. Sundvik, "Long range acoustic imaging of the Continental Shelf Environment reveals massive fish schools: 2003 Main Acoustic Clutter Experiment", submitted to the Acoustical Society of America for 146th Meeting in Austin, TX, Nov 2003.

[C17] D. T. Symond, P. Ratilal and N. C. Makris, "Fish Schools are the dominant cause of long range active sonar clutter in the New Jersey Continental Shelf: Quantitative Correlations", submitted to the Acoustical Society of America for 146th Meeting in Austin, TX, Nov 2003.

[C18] P. Ratilal, S. Lee and N. C. Makris, "Range-dependent reverberation modeling with the parabolic equation," submitted to the Acoustical Society of America for 146th Meeting in Austin, TX, Nov 2003.

[C19] Y. Lai, S. Lee, P. Ratilal and N. C. Makris, "Comparison of modeled and measured sonar returns from calibrated targets in the Main Acoustic Clutter Experiment 2003," submitted to the Acoustical Society of America for 146th Meeting in Austin, TX, Nov 2003.

[C20] T. Chen, P. Ratilal and N. C. Makris, "Time delay and Spread in the Mean Forward Propagated Signal due to Scattering from Random Inhomogeneities," submitted to the Acoustical Society of America for 146th Meeting in Austin, TX, Nov 2003.

[C21] P. Ratilal and N. C. Makris, "Covariance of the forward propagated field through a waveguide containing random inhomogeneities," submitted to the Acoustical Society of America for 146th Meeting in Austin, TX, Nov 2003.

HONORS/AWARDS/PRIZES

The following have been awarded to Dr. Ratilal.

- Office of Naval Research (ONR) Postdoctoral Award in Ocean Acoustics (2002)
- Best Student Paper Awards in Underwater Acoustics, Acoustical Society of America Meetings

- Fall 2001, Fort Lauderdale, FL
- Fall2000, NewportBeach, CA
- Spring 2000, Atlanta, GA

- DSO National Laboratories Graduate Scholarship, Singapore (1998)